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CONTROL OF FLOW SEPARATION AND MIXING BY AERODYNAMIC EXCITATION

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Abstract

The recent research progress in the control of shear flows using unsteady aerodynamic excitation conducted at the NASA Lewis Research Center is reviewed. The program is of fundamental nature concentrating on the physics of the unsteady aerodynamic processes. This field of research is a fairly new development with great promise in the areas of enhanced mixing and flow separation control. Enhanced mixing research reported in this paper include influence of core turbulence, forced pairing of coherent structures, and saturation of mixing enhancement. Separation flow control studies included are for a two-dimensional diffuser, conical diffusers, and single airfoils. Ultimate applications of this research include aircraft engine inlet flow control at high angle of attack, wide angle diffusers, highly loaded airfoils as in turbomachinery, and ejector/suppressor nozzles for the supersonic transport. An argument involving the Coanda Effect is made here that all of the above mentioned application areas really only involve forms of shear layer mixing enhancement. The program also includes the development of practical excitation devices which might be used in aircraft applications.

Introduction

The shadowgraph pictures of Brown and Roshko[1] suggest that coherent structures may control the mixing dynamics in a free shear layer. The linear stability analysis of Michalke[2,3] provides a quantitative description of how these structures originate out of small disturbances. Many papers have been written describing extensive experimentation and analysis on this phenomena. It is not intended here to review this vast literature. Wygnanski and Peterson[4] and Hussain[5] have written extensive recent reviews on coherent structures and motion in free shear layers. The objective of this paper is to review the recent progress of the Shear Flow Control Program at NASA Lewis which is based upon controlling the steady flow through the use of the natural instabilities of the flow. Small aerodynamic disturbances can be used to trigger the growth of the coherent structures which in turn dominate the mixing process. The NASA Lewis program, which grew out of the earlier program on jet noise reduction, was first reported by Stone and McKinzie[6] in June 1984. The October 1987 paper of Rice and Zaman[7] provided a progress summary, program element description, and a literature review of the research relevant to the work.

This review will begin with a discussion of the overall separation-reattachment process providing an argument that it's control is very closely related to mixing control in a free shear layer. With this argument established, it is suggested that our program has a common thread, mixing enhancement, such that progress in one area will apply to all of our program elements. Recent progress in our axisymmetric jet excitation program will then be covered. This includes studies of the influence of core turbulence on receptivity, enhanced jet mixing due to forced coherent structure pairing, comparisons with recent theoretical calculations on jet mixing, and a review of the current and future work in this area. Results of the studies of separation control in diffusers will then be presented. These include a low velocity, two-dimensional diffuser and a series of conical high velocity diffusers which are in the early stages of flow control demonstration. Separation control research on a single airfoil at low to moderate Reynolds number will then be presented. A dramatic increase in lift results from excitation of this airfoil flow. A recently discovered low frequency intense oscillation of the flow around a highly loaded airfoil is discussed next. The results of acoustic excitation of a jet with swirling flow are then presented. The paper is concluded with a discussion of excitation devices which may be relevant to practical applications.

The shear flow control covered in this paper might be referred to as open loop control which takes advantage of the natural flow instabilities in the flow. This is contrasted to closed loop control which uses a measured signal to provide an input into the flow through a transducer or actuator. The latter is not currently part of our program but might be included in the future.

Mechanics of Reattachment with Excitation

An excellent flow visualization photograph published by Ahuja, et al.[8] is reproduced in Fig. 1. In Fig. 1(a) the flow over the airfoil at high angle of attack (26°) is shown to be separated at a very short distance downstream from the stagnation point. The tube from the acoustic driver used to excite the flow is shown in the upper left corner of the figure. A glass bead boundary layer trip is pointed out in Fig. 1(b) and is present in both flow visualization photographs ensuring a turbulent boundary layer in both cases. In Fig. 1(b) when the acoustic excitation is turned on the flow is seen to remain nearly attached over most of the airfoil. Although this demonstration was for only a single airfoil, it does not take much imagination to visualize this same phenomena occurring at an aircraft inlet lip at high angle of attack, in a very short flow diffuser, or even in turbomachinery blading at high loading.

The phenomenon present in the reattachment process shown in Fig. 1 was not really explained in Ref. 8. An attempt is made here to offer a rational explanation of the global process occurring when excitation causes a reattachment of the flow.

In Fig. 2 two jets are shown. In Fig. 2(a) the jet is isolated from any surface or obstruction and the flow is axisymmetric with equal pressure and entrainment flow circumferentially around

the jet. In Fig. 2(b) a surface is shown below the jet which restricts the free entrainment flow into the shear layer of the jet. The shear layer pulls fluid from this lower restricted region through turbulent mixing but this fluid can not easily be replenished due to the flow restricting influence of the lower plane. The pressure is thus reduced much more in this region than in the unrestricted region above the jet and the pressure gradient thus forces the jet to bend down toward the surface. This is a form of the Coanda Effect which will now be used to explain the reattachment phenomena due to shear layer excitation.

In Fig. 3(a) a flow situation is shown with the solid surface quickly curving away from the general flow direction and the flow thus separates near the initial curvature just as the flow separated on the airfoil of Fig. 1(a). A relatively dead flow region occurs in the separation region with flow being continuously extracted due to the turbulent mixing process in the shear layer formed between this dead region and the outer ambient flow If this were a two-dimensional flow (extremely long span) the only place for the replacement fluid to come from is far downstream at the ultimate reattachment point, or if the surface were cut off as in a diffusing nozzle, from the outside ambient region. If the configuration has finite span, of course the fluid could also flow in from the ends. With the extracted fluid moving toward the outer ambient fluid and the replacement fluid coming mainly back upstream from the reattachment point or the pressure relief point, the rotational flow pattern familiar for separated flow is established as shown in Fig. 3(a). The pressure is also reduced in this separated region due to the shear flow fluid extraction and the restricted fluid replacement. The pressure gradient bends the flow down toward the surface and all of these processes continue to build until an equilibrium (most likely unstable) is established.

Now if the mixing rate in the shear layer is increased by the proper excitation of the shear layer instabilities, the flow situation as in Fig. 3(b) will occur. The additional fluid extraction due to increased mixing will further draw down the pressure in the separation region. The increased pressure gradient will further bend the fluid toward the surface causing the separated region to shorten. Further increases in mixing rate in the shear layer will accentuate the process and further decrease the separated region size. If the above described phenomena were responsible for the reattachment process due to excitation then one measurable result would be a drastic reduction of the static pressure in the separation region very near to the point of separation. This will indeed be seen to be the case later in this paper when the two-dimensional diffuser is discussed. The main difference between the geometry discussed in Fig. 3 and the airfoil in Fig. 1 is that the flow over the airfoil at such a high angle of attack never does completely reattach, the same as for a rapidly diffusing nozzle commented upon in regard to Fig. 3. However, the increased mixing in the shear layer due to the acoustic excitation still extracts additional fluid from the separation region, pulls down the static pressure, and curves the flow toward the airfoil. The lower pressure near the separation point probably accounts for the increased lift and also helps in providing the additional replacement fluid flow back up through the restricted flow path near the surface.

This somewhat lengthy discussion of the Coanda Effect to explain the reattachment process in the flow shown in Fig. 1 also serves another useful purpose. If the phenomena are indeed as described, then the separation control process is really just another manifestation of the shear layer mixing process and research results from jet mixing enhancement studies should carry over to help separation control progress and vice-versa.

Jet Mixing Enhancement With Excitation

Most of the emphasis here will be on fairly fundamental experiments involving the jet mixing process with acoustic drivers used to excite the shear layer instability. The data were taken in the jet excitation rig shown in Fig. 4 taken from Ref. 9. The jet diameter was 8.8 cm and the jet core flow was very clean with a turbulence level of something less than 0.15 percent of the jet velocity. Unless otherwise specified, a boundary layer trip was located 33 cm upstream of the nozzle exit to ensure a turbulent boundary layer. The four acoustic drivers in vent cans are also seen in Fig. 1. At the low frequencies used here, only the plane wave mode survives the propagation through to the nozzle exit. A three-dimensional traversing table is seen in the foreground which is used to move the instrument probes. More detailed information can be found in the references which follow in the discussion. As mentioned above, the emphasis here is on the information gained from the experiments. Only those theoretical results which have been directly integrated into the program by comparison with data will be discussed here.

Core Turbulence Effect on Jet Excitability

Since most real jets in practice have fairly high initial turbulence levels but many laboratory jets for research have low turbulence levels, it is of interest to determine what effect this level has on the excitability of a jet. The experiment of Raman[10], et al., used a series of grids across the flow located 33 cm upstream of the nozzle exit to control the jet core turbulence. The jet exit flow had a uniform or top-hat velocity profile with a nearly uniform turbulence profile that could be adjusted from 0.15 to 5 percent. The initial boundary layer was turbulent (with the trip) with a shape factor of 1.6, a momentum thickness of 0.006 of the jet diameter, and a turbulence level of about 7 percent for all cases. The exception was a laminar or transitional case in which no trip was used and the boundary layer had a higher shape factor and a higher velocity perturbation near the wall. Figure 5 shows the evolution of the excitation fundamental along the axis of the jet. This is the trace of the velocity perturbation produced on the jet axis by the passing coherent structure forced by the excitation. The excitation level at the jet exit was held at about 0.5 percent of the jet velocity. It can be seen that higher turbulence level suppresses the initial growth of the instability wave, reduces the maximum level which the coherent structure can attain and moves the peak downstream. The laminar boundary layer case does not fit the pattern seen for the turbulent boundary

layer cases and points out the importance of knowing the initial conditions for this type of experiment. Figure 6 shows that the jet mixing enhancement due to excitation has also been suppressed by the higher core turbulence levels. The two curves for each turbulence level represent the jet centerline velocity evolution along the axis for the excited and unexcited cases. A large difference between these two curves indicates a large drop in jet velocity (and presumably an increase in mixing) due to the excitation. Again the laminar case does not fit the trend of the other data. Large instability in the laminar boundary layer has apparently excited the jet mixing process and there is little extra benefit that the acoustic excitation can provide. It should be mentioned here that for the unexcited jet with turbulent boundary layer, with core turbulence level varied from 0.15 to 5 percent of the jet velocity, there was no difference in jet mixing as measured by either the centerline velocity or the jet diameter at the half velocity points.[10] All of the data in Figs. 5 and 6 were obtained at the Strouhal Number, S_T, for maximum excitation effect. This nondimensional number is defined as frequency*jet diameter/jet velocity.

Mankbadi[11], et al., modified the theoretical development of Mankbadi and Liu[12] to allow a uniform jet core turbulence in the theory. This approximate theory assumes the instability mode shape to be given by the linear stability theory based on the local velocity profile. An ordinary differential equation results providing a description of the instability wave evolution while considering the interaction of the instability wave, the steady flow, and the turbulence. These theoretical results from Ref. 11 are compared to the data in Fig. 7. The data is the same as shown in Fig. 5. The trend in the evolution of the instability wave is seen to be faithfully reproduced but the theoretical values are seen to be somewhat higher. This difference may be due to the fact that the theory contains only the fundamental of the excitation. In the experiment a subharmonic evolves which may represent pairing of the coherent structures which extracts energy from the fundamental and alters the energy interchange between the steady flow, the sinusoidal waves, and the random turbulence. With further development, the theory certainly appears promising.

Mixing Saturation with Single Frequency Plane Wave Excitation

There seemed to be a limitation on the coherent structure amplitude and the jet mixing enhancement which could be obtained using single frequency plane wave acoustic excitation. The phenomenon of saturation has been discussed by Crow and Champagne[13]. This saturation effect was systematically explored in experiments reported by Raman[9], et al. The jet centerline velocity was measured at 9 diameters downstream (x/D = 9) both with and without excitation and the ratio U_{ex}/U_{ux} taken. If this ratio is near unity there is no influence of excitation upon the mixing which would reduce the centerline velocity. As the ratio decreases, mixing enhancement is occurring due to excitation. This velocity ratio is shown in Fig. 8 as a function of excitation velocity amplitude at the nozzle exit divided by the jet velocity for three steady flow Mach numbers. As the excitation level is increased from zero to about 0.25 percent, the mixing enhancement is apparent. However, as the excitation level approaches about 0.5 to 1 percent the mixing levels out and reaches a saturation level of about $U_{ex}/U_{ux} = 0.81$. As another measure of mixing enhancement, the momentum thickness of the jet mixing layer, at nine jet diameters downstream, was explored. Again the ratio of excited to unexcited momentum thickness was taken and is displayed in Fig. 9 as a function of excitation velocity level. This measure of mixing enhancement also shows a saturation level is reached at about 0.5 to 1 percent excitation level. Again the approximate energy integration technique of Mankbadi and Liu[12] was used in Ref. 9 to calculate the theoretical curve shown in Fig. 9. The theory is seen to be very good in trend with a small underprediction in level.

It must be emphasized here that the mixing saturation results shown so far are valid for **single frequency plane wave excitation only**. With such excitation, the saturation data might lead to the conclusion that mixing enhancement by excitation may be extremely limited. This is **not** a valid conclusion and can be refuted immediately using the information of the next section on two frequency excitation.

Two Frequency Excitation-Forced Pairing

In an attempt to overcome the saturation limitation of single frequency plane wave excitation, a study of two frequency excitation was conducted by Raman and Rice[14]. The experiment still contained only plane wave excitation but the two frequencies allowed the possibility of forced pairing of the coherent structures with an increase in mixing. Several studies have been made involving subharmonic development and excitation and the reader is referred to Ref. 14 for a fairly complete list. The publication of Mankbadi[15] provided theoretical results, for the axisymmetric jet of interest, which showed a potential for large increases in mixing enhancement but large amplitude excitation seemed to be needed, on the order of 3 percent of the jet velocity. Large levels of required excitation might be expected since the forced pairing process is nonlinear. This level is higher than the 1 percent level of saturation discussed in the previous section. Electropneumatic drivers were required in Ref. 14 to attain these high excitation amplitudes.

A very interesting set of data from Ref. 14 is shown in Fig. 10. The evolution of the velocity trace on the jet axis due to the passing coherent structures is shown for the fundamental and the subharmonic. Both signals are present in the excitation at the jet exit with a fundamental to subharmonic amplitude ratio of 15, Strouhal numbers of 0.4 and 0.2, and a phase between them of 270°. Note that at a fundamental excitation level of 1 percent, not much interesting interaction is observed. Recall that this level is high enough to saturate the fundamental as observed in the previous section. As the fundamental excitation level is increased (thus also the subharmonic since the ratio is constant) an interaction occurs which drives the subharmonic to extremely high level (about 18 percent of the jet velocity). Note that at the higher levels the fundamental amplitude falls off from the jet exit before increasing again. This can be explained as follows. Near the jet exit the hot wire measures the

acoustic field velocity which falls off in some complicated manner due to the complex near field. At about one jet diameter ($x/D = 1$) the hydrodynamic field of the coherent structure has grown sufficiently to dominate the velocity measurement from there on. At an excitation level somewhere between 3.4 and 5.7 percent, the forced pairing process itself has saturated.

The jet centerline steady flow velocity evolution is shown in Fig. 11 for the same conditions as the data in Fig. 10. Note that at the lowest level (1 percent) the saturated fundamental has some influence on the potential core. Looking back at Fig. 6 it is seen that for conditions without much excitation effect, the potential core (about out to $x/D = 4$) is relatively unaffected. For the higher excitation levels the potential core is demolished indicating a drastic alteration of the mean flow.

The final data in this sequence, Fig. 12, are extremely interesting. From left to right (a to d) the data represent, (a) the fundamental frequency only at Strouhal number of 0.6, excitation level of 3 percent of jet velocity, (b) the subharmonic only at Strouhal number 0.3, excitation level 0.2 percent of jet velocity, (c) both frequencies with a 180° initial phase between them at the jet exit, and (d) both frequencies with a 0° phase between them. Notice that when the phase is favorable the subharmonic growth is extremely large, case (c). When the phase difference is not favorable, the subharmonic generation is suppressed, case (d). When the harmonic growth is large, the mixing is enhanced considerably. When the subharmonic is suppressed, the mixing reverts to that of the fundamental alone.[14]

Note that all of the above was accomplished with plane wave excitation only. There is an indication that as the shear layer thickens toward the end of the potential core, the most unstable mode would more likely be a three-dimensional helical mode.[3] Thus the subharmonic most likely to enhance mixing should be excited in this mode. Our current work in this area is aimed at achieving this capability using eight externally mounted acoustic drivers properly phased to excite the desired mode, and a ring of eight cross films to measure the modal content as it evolves down the jet. System checkout and calibration is currently in progress and it is anticipated that some results will be reported soon.

Diffuser Separation Control Using Excitation

An experiment to study the control of separation in a low speed diffuser is shown in Fig. 13(a). This 20° one sided diffuser ramp is located in a tunnel 50.8 cm high and 76.2 cm wide with a flow in this case of 5 m/sec. Static pressure taps are located near the center of the ramp all along the axial length. The unsteady excitation is introduced by an oscillating vane located right at the down turn of the upper surface. Maximum vane oscillation used was about 3.2 mm (0.125 in.). Three sets of data are shown in Fig. 13(b) where pressure coefficient along the surface is plotted. Before discussing this data it should be pointed out that for complete separation of the flow which reattaches well downstream from the ramp, the pressure coefficient is nearly constant at a value of zero. This was observed for a lower velocity and an approach boundary layer which was laminar (not shown here). At the higher velocity shown here and with a turbulent boundary layer, the flow partially reattaches on the ramp which can be seen from the circle data points indicating no excitation. This is probably due to the excitation effect of the natural turbulence causing an increase in mixing in the separated free shear layer near the separation point. As the excitation is turned on and increased in frequency toward the maximum instability frequency in the shear layer, the reattachment of the flow is improved as evidenced by the square data points which are approaching the ideal pressure coefficient (flow completely attached) of 0.28 near the end of the ramp. Also note that with improved mixing in the shear layer, a low pressure region develops just downstream from the oscillating vane as anticipated earlier from the discussion of the Coanda Effect and separation control. The pressure deficit caused by the mixing can be seen to reach upstream from the maximum mixing region which causes an acceleration of the boundary layer toward the mixing region. Some very interesting unsteady velocity data has been taken with a corona probe which measures velocity in both directions. These data include velocity probability density functions which show the fraction of the time the flow travels is each direction. This data taken at several distances off the ramp surface, at several axial locations, and both with and without excitation will be published in the near future.

A higher velocity conical diffuser has also been studied by Zaman and Dahl[16]. The throat Mach number was varied from 0.05 to 0.95 and the throat diameter was 5.08 cm. The total cone angles studied were 16, 20 and 24°. Most of the effort concentrated upon the separation phenomenon itself with acoustic excitation used extensively only with the 16° diffuser. Unfortunately this diffuser had large separation only for low Mach number below 0.2 where apparently a laminar separation occurred similar to that in the two-dimensional diffuser commented upon in the previous paragraph. For these low velocity cases, excitation did reduce the velocity fluctuations due to separation and improved the pressure recovery coefficient by as much as 12 percent. Additional excitation work on the higher angle diffusers will be carried out and reported.

Airfoil Separation Control

Excitation of the separated flow over an airfoil also results in separation improvement as illustrated in Fig. 1.[8] Zaman and McKinzie[17] have conducted research on the control of laminar separation over airfoils using the same low velocity wind tunnel as referred to above in the two-dimensional diffuser studies. The research was conducted using two types of airfoil, the LRN and the Wortmann airfoils. Significant improvements in lift were reported when the flow was properly excited with acoustic drivers. A set of data are shown in Fig. 14. The abscissa is the resultant excitation velocity amplitude in the incoming flow normalized by the ambient velocity. It is interesting to note that a saturation effect is observed, much like that of the free jet mentioned earlier, when the excitation velocity amplitude is large. Measurements in the flow indicated that the instability growth occurred in the separated

shear flow region ruling out boundary tripping as the dominant mechanism. A correlation for most effective excitation was found which was valid for both airfoils over the chord Reynolds number, R_c, range studied from 25 000 to 100 000. This frequency scaled as $St/R_c^{1/2} = 0.02$ to 0.03, where Strouhal number, St, is frequency*chord/ambient velocity.

Another interesting study was conducted by Zaman,[18] et al. concerning the low frequency oscillation of the flow around a highly loaded airfoil. This oscillation occurs at about one-tenth the frequency but with a lift fluctuation perhaps 50 times that of the more familiar bluff body separation. This phenomenon is very significant since it may be responsible for dynamic stall and buffeting of highly loaded airfoils. An intermittent separation and reattachment of the flow on the suction surface of the airfoil seems to be responsible for the oscillation, but the details of the frequency scaling have yet to be worked out. The oscillation can be controlled using high frequency excitation.

Much more fundamental work must be done regarding the control of flow separation over airfoils. The similarity to the diffuser flow can probably benefit both areas of research, and the basic free shear layer research should help to define mechanisms for the entire field of study. When sufficient background work has been accomplished, shear flow control will be extended to applications which benefit the flow in turbomachinery.

Excitation of Swirling Flows

The swirling jet flow part of our program will be covered elsewhere in this program by Farokhi[19], et al., so only brief comments will be made here regarding the excitation portion of the program. The jet facility shown in Fig. 4 contains three-manifolds with circumferentially pointing nozzles at different radii from the plenum axis. Control of the flow in these three-manifolds can provide variability in the swirl flow profile from nearly free vortex to forced vortex flow. An initial study of excitation of swirling flow was conducted by Taghavi[20], et al., on a jet with a fairly high swirl number, S = 0.35, where S is the ratio of tangential momentum to axial momentum measured at the jet exit. Plane wave excitation was used provided by four electromagnetic drivers as pictured in Fig. 4. The single frequency hydrodynamic instability wave was observed to grow in the axial direction but it attained only half the amplitude and peaked out at about half the axial distance as for a nonswirling jet. The mean flow was unaffected by the excitation. A second study by Taghavi[21], et al., at a lower swirl number of S = 0.12, employed higher excitation amplitude using two electopneumatic drivers. In this case the jet half-velocity radius and the momentum thickness at seven nozzle diameters downstream were increased by 13.2 and 5.8 percent respectively. However, when the swirl number was increased to 0.18, again no effect of excitation on the mean flow was observed. In both of the studies above the Strouhal number for maximum instability wave growth was about 0.4, about the same as for a nonswirling jet. Future studies in this area will employ the eight external drivers mentioned earlier in regard to the free jet research. This will allow transverse modes to be used for excitation of the swirling jet to study vortex breakdown and mixing modification.

Excitation Devices

In all of the experiments discussed above, the excitation devices were acoustic drivers or, in the case of the two-dimensional diffuser, an oscillating vane. Lower amplitude cases used electromagnetic drivers while high amplitude examples employed electropneumatic drivers of the 4000 W level. These devices are fine for laboratory experiments the latter being powerful enough for just about any conceived experiment. However, when ultimately real applications are considered, much more simple compact devices must be developed. Ideally these devices would not have any moving parts, would not need external power, and would fit nicely into the device that they are to control. Obviously electric drivers do not fit these requirements but some fluidic oscillators do. The flow over simple slots have been studied extensively.[22-24] A compartmented slot could be located inside a nozzle with some kind of "tickler" control on each compartment to control mode phase which would be essential for example with supersonic flow. Multiple flip-flop jet nozzles as studied by Viets[25] or perhaps some form of the whistler nozzle studied by Hussain[26] seem to be promising candidates.

Concluding Remarks

This paper has concentrated on reporting the recent progress in the NASA Lewis Shear Flow Research Program. The program is of fundamental nature with a long term outlook. Several very basic elements of our program have been reviewed here. The potential for shear flow control appears positive. Much more work needs to be conducted to define opportunities and limitations in this area. The research should have several side benefits such as unsteady numerical code validation, improved understanding of turbulence, and improved turbulence models. At any given time the current knowledge can be brought to bear on urgent problems such as supersonic jet noise control or inlet separation control.

Many fine research efforts, out of necessity and original intent, have been left out of this paper. Several academic institutions and some private company research laboratories have excellent programs in this area as evidenced by several days of presentations at the AIAA Shear Flow Conference in March 1989. In the spirit of the more limited scope of this paper, only the work connected directly to our in-house program has been included.

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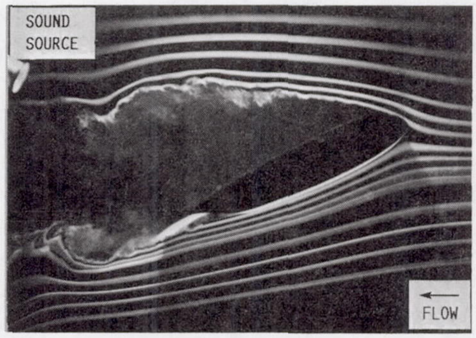

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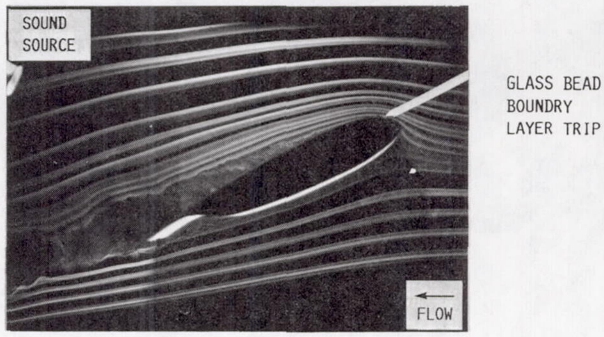
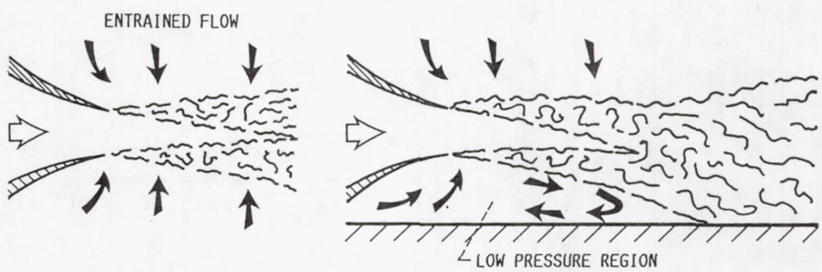


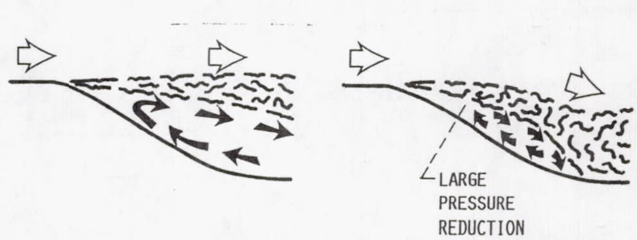
(b) EXCITED.

FIGURE 1. - EFFECT OF ACOUSTIC EXCITATION ON AIRFOIL FLOW SEPERATION; ANGLE OF ATTACK, 26 DEG.; FREE STREAM VELOCITY, V_0 = 13 M/SEC; EXCITATION FREQUENCY, f_e = 640 Hz.



(a) ISOLATED JET. (b) JET NEAR WALL.

FIGURE 2. - THE COANDA EFFECT DUE TO A SURFACE LOCATED NEAR A JET



(a) NO EXCITATION. (b) MODERATE EXCITATION.

FIGURE 3. - CHANGE IN SEPERATION FLOW PATTERNS DUE TO EXCITATION.

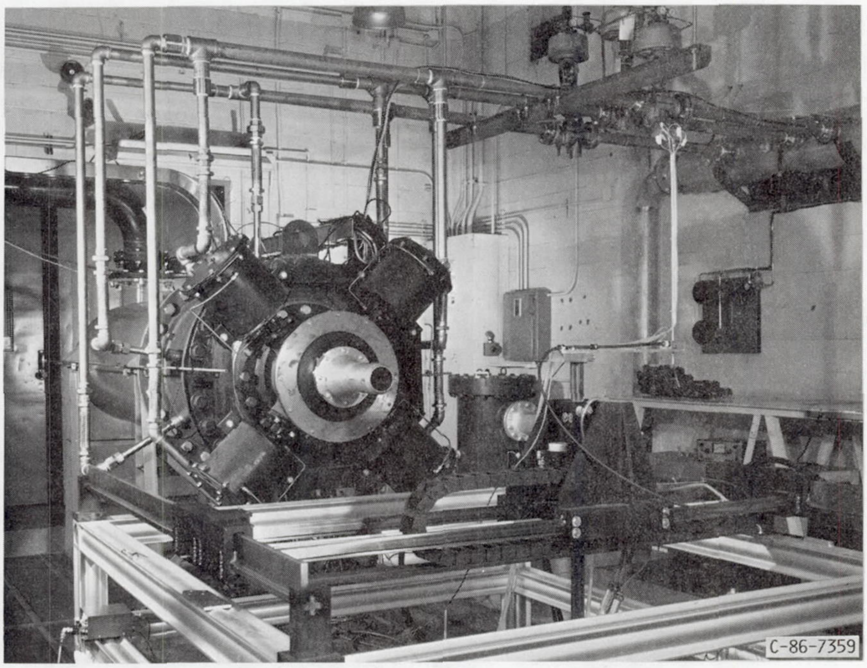


FIGURE 4. - JET FACILITY AND TRAVERSING MECHANISM.

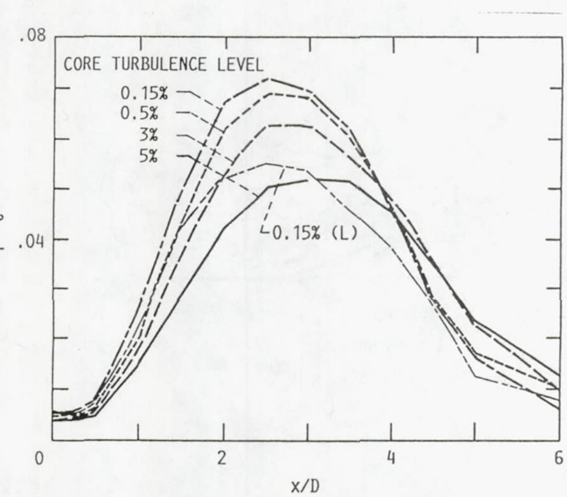


FIGURE 5. - VARIATION OF THE FUNDAMENTAL RMS VELOCITY FLUCTUATION (u_f') ALONG THE JET AXIS, M = 0.3, S_T = 0.47 (537 Hz).

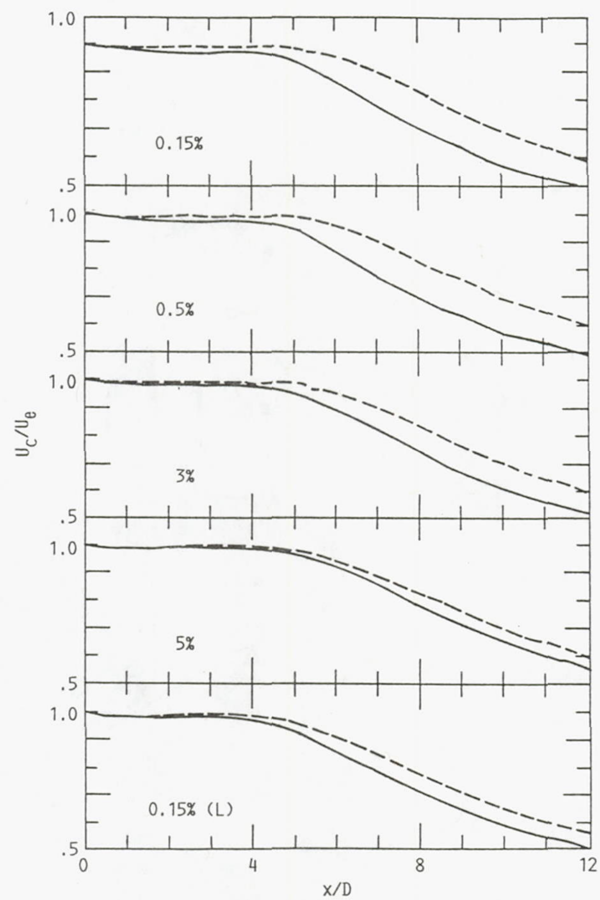


FIGURE 6. - VARIATION OF U_c AT M = 0.3 FOR THE FIVE CASES AS INDICATED: ------, NO EXCITATION; ———, EXCITATION AT ST = 0.47 (537 Hz), L_e = 130 dB.

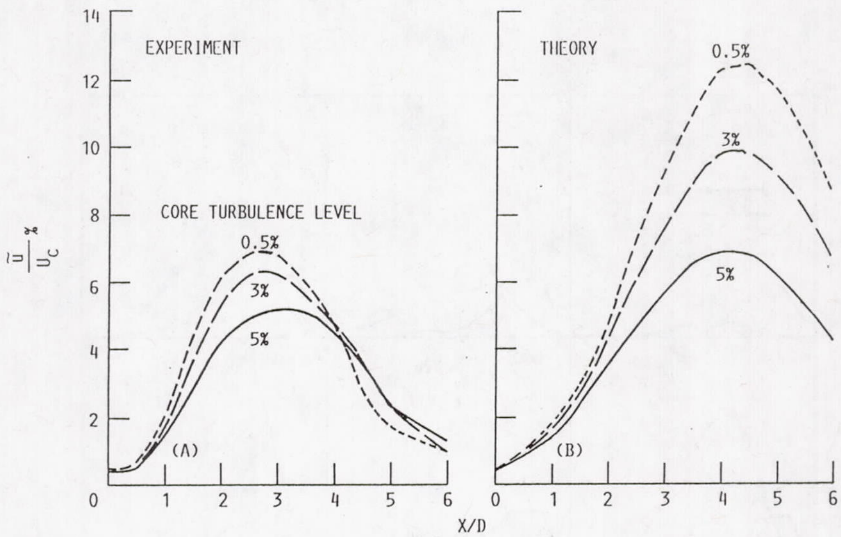


FIGURE 7. - DEVELOPMENT OF THE FUNDAMENTAL COMPONENT ALONG THE JET AT SEVERAL INITIAL LEVELS OF TURBULENCE.

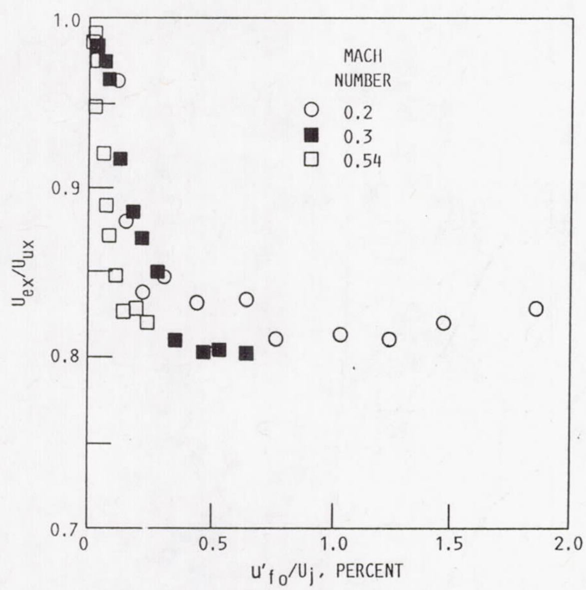


FIGURE 8. - VARIATION OF THE MEAN VELOCITY MEASRUED AT x/D = 9 ON THE JET CENTERLINE WITH THE LEVEL OF EXCITATION FOR VARIOUS MACH NUMBERS.

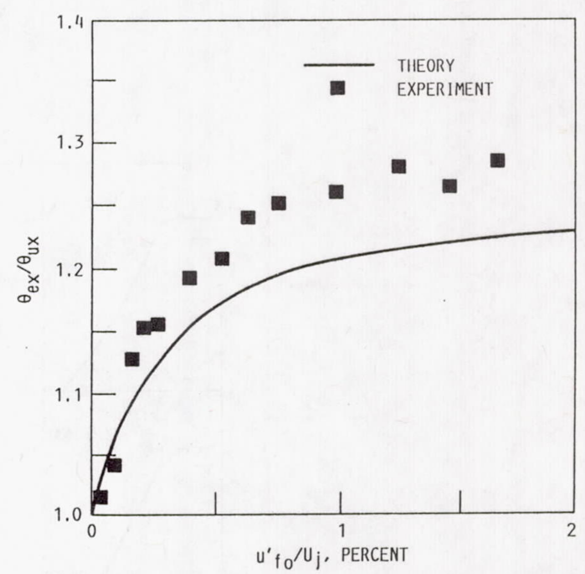


FIGURE 9. - COMPARISON OF EXPERIMENT VERSUS THEORY FOR THE VARIATION OF MOMENTUM THICKNESS AT x/D = 9 WITH THE INITIAL LEVEL OF EXCITATION, (St = 0.5, M = 0.2).

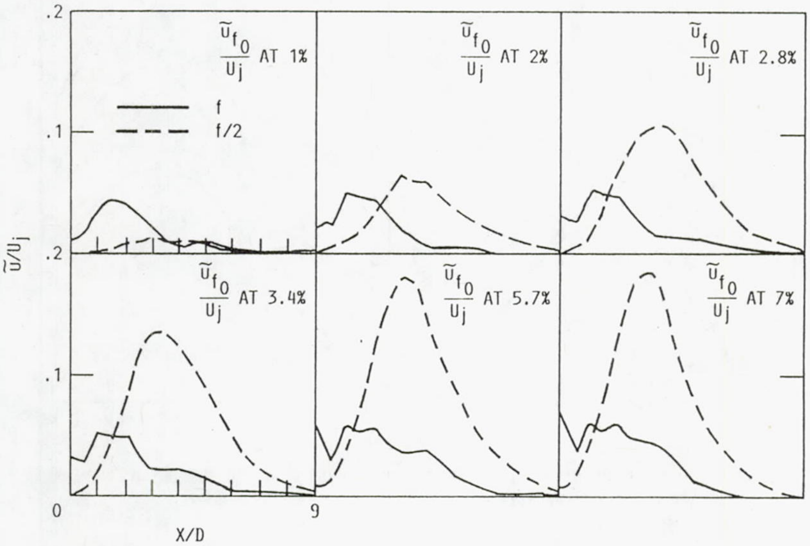


FIGURE 10. - AXIAL EVOLUTION OF PHASE-AVERAGED UNSTEADY VELOCITY COMPONENTS ON THE JET CENTERLINE FOR VARIOUS INITIAL LEVELS OF EXCITATON. (St = 0.2, 0.4, $\varphi_0 = 270^0$, $\tilde{u}_{f_0}/\tilde{u}_{f/2_0} = 15$, M = 0.45.)

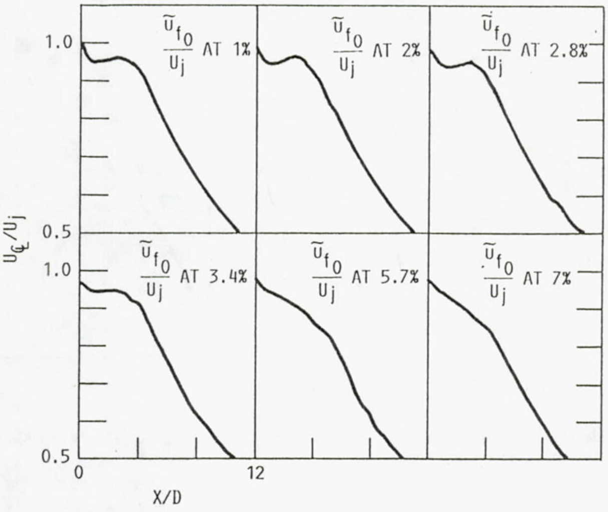
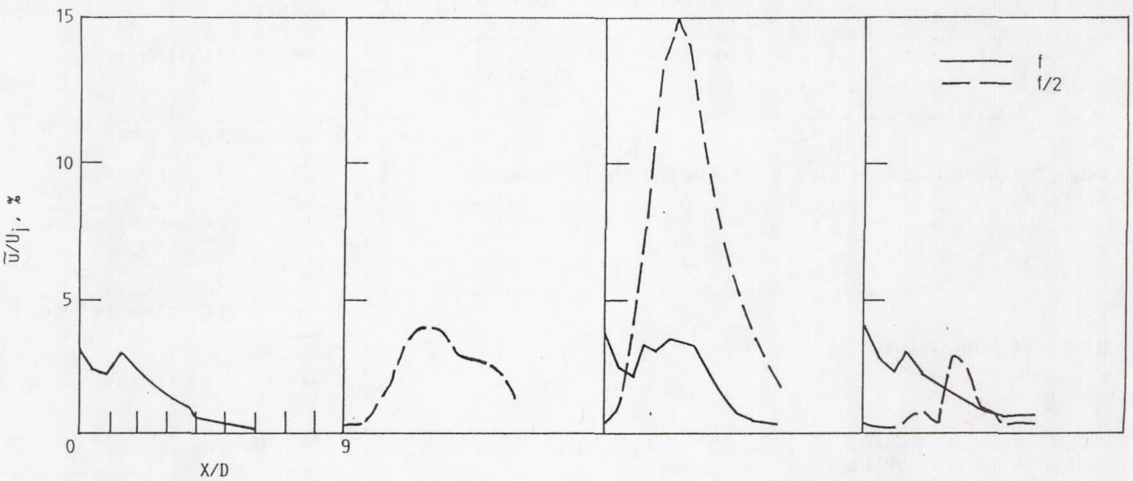


FIGURE 11. - EFFECT OF INCREASING INITIAL LEVELS OF EXCITATION ON THE JET CENTERLINE MEAN VELOCITY. (St = 0.2, 0.4, $\varphi_0 = 270^0$, $\tilde{u}_{f_0}/\tilde{u}_{f/2_0} = 15$, M = 0.45.)



(a) St = 0.6, $\tilde{u}_{f_0}$ = 0.03 U_j. (b) St = 0.3, $\tilde{u}_{f/2_0}$ = 0.002 U_j. (c) St = 0.3, 0.6, φ_0 = 180°, $\tilde{u}_{f_0}$ = 0.03 U_j, $\tilde{u}_{f/2_0}$ = 0.002 U_j. (d) St = 0.3, 0.6, φ_0 = 0°, $\tilde{u}_{f_0}$ = 0.03 U_j, $\tilde{u}_{f/2_0}$ = 0.002 U_j.

FIGURE 12. - SUBHARMONIC AUGMENTATION AND SUPPRESSION DUE TO INITIAL PHASE DIFFERENCE (M = 0.2).

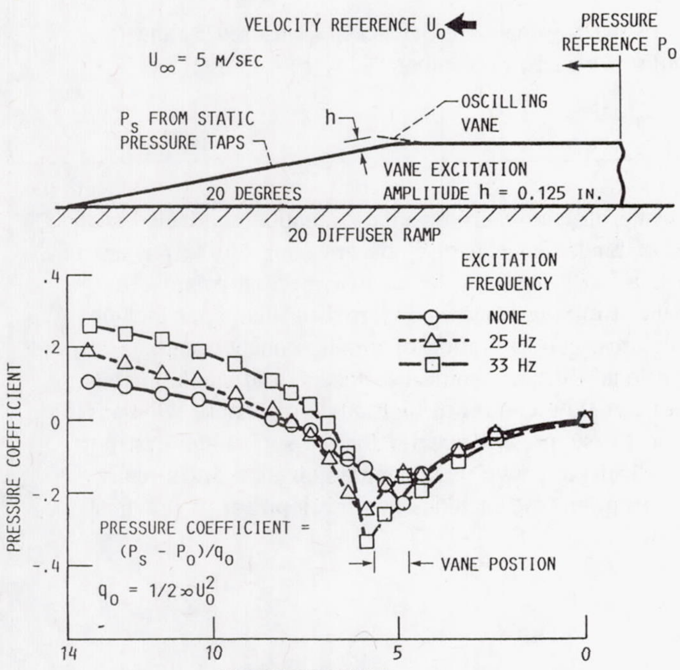


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FIGURE 13. - CONTROL OF SEPARATION ON A TWO DIMENSIONAL DIFFUSER.

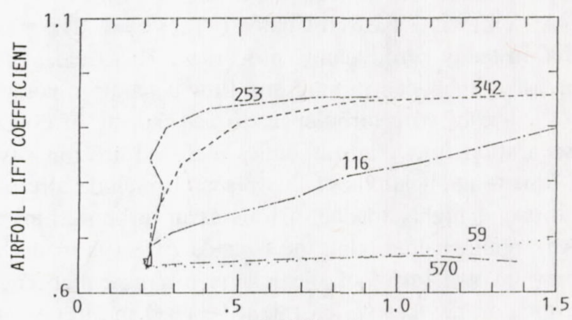

FIGURE 14. - EXCITATION AMPLITUDE EFFECT ON LIFT COEFFICIENT AT INDICATED EXCITATION FREQUENCY (Hz), LRN AIRFOIL AT 6° ANGLE OF ATTACK AND REYNOLDS NUMBER = 50,000.

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15. Supplementary Notes

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16. Abstract

The recent research progress in the control of shear flows using unsteady aerodynamic excitation conducted at the NASA Lewis Research Center is reviewed. The program is of fundamental nature concentrating on the physics of the unsteady aerodynamic processes. This field of research is a fairly new development with great promise in the areas of enhanced mixing and flow separation control. Enhanced mixing research reported in this paper include influence of core turbulence, forced pairing of coherent structures, and saturation of mixing enhancement. Separation flow control studies included are for a two-dimensional diffuser, conical diffusers, and single airfoils. Ultimate applications of this research include aircraft engine inlet flow control at high angle of attack, wide angle diffusers, highly loaded airfoils as in turbomachinery, and ejector/suppressor nozzles for the supersonic transport. An argument involving the Coanda Effect is made here that all of the above mentioned application areas really only involve forms of shear layer mixing enhancement. The program also includes the development of practical excitation devices which might be used in aircraft applications.

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